THE CHANDRA DEEP FIELD-NORTH SURVEY. XVI. THE X-RAY PROPERTIES OF MODERATE-LUMINOSITY ACTIVE GALAXIES AT $Z > 4$

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ABSTRACT

We present X-ray spectral analyses of the three $z > 4$ Active Galactic Nuclei (AGNs) thus far spectroscopically identified in the *Chandra* Deep Field-North Survey, at redshifts of 5.186, 4.424, and 4.137. These analyses are made possible by the extremely deep exposure ($\approx$ 2 Ms) and the low *Chandra* background. The rest-frame $\approx$ 2.5–40 keV spectra are the first for optically faint (two of the three sources have $I > 24$) $z > 4$ AGNs. The $z = 5.186$ quasar is well fitted by a power-law model with photon index $\Gamma = 1.8 \pm 0.3$, consistent with those of lower-redshift, unobscured AGNs. The other two AGNs have flatter effective X-ray photon indices ($\Gamma \approx 1.1$–1.5), suggesting the presence of intrinsic absorption (provided their underlying X-ray continua are similar to those of lower-redshift AGNs). It is possible that the flat X-ray continuum of the $z = 4.424$ AGN is partially related to its radio loudness. If the $z = 4.137$ AGN suffers from X-ray absorption, the implied column density is $N_{\rm H} \approx 2 \times 10^{23}$ cm^{-2}.

Subject headings: galaxies: active — galaxies: nuclei — quasars: general — surveys — X-rays: galaxies

1. INTRODUCTION

One of the most challenging goals in modern astronomy is to investigate the nature of the first objects to form at the end of the "Dark Age" (i.e., at the reionization epoch; e.g., Rees 1999; Loeb & Barkana 2001). From an X-ray perspective, there is increasing evidence that Active Galactic Nuclei (AGNs) are powerful X-ray emitters in the early Universe (e.g., at $z > 4$; Kaspi, Brandt, & Schneider 2000; Vignali et al. 2001, 2003, hereafter V01 and V03; Brandt et al. 2002a,b) as well as locally. However, to date X-ray spectral analysis at $z > 4$ has only been possible for the most optically luminous quasars (e.g., $M_{\rm B} \approx -27$ to -30; V03), which are presumably only a minority of the AGN population.

In this study we use the 2 Ms exposure of the *Chandra* Deep Field-North (CDF-N) to constrain the X-ray properties of three moderate-luminosity $z > 4$ AGNs. This is the first direct X-ray spectral analysis performed on $z > 4$ radio-quiet AGNs with more than 100 counts (two of the three sources). Indeed, constraints on the X-ray properties of moderate-luminosity AGNs at the highest redshifts via X-ray spectral analysis can only be placed by deep X-ray surveys at present. The moderate-luminosity and presumably moderate-mass AGNs found in the CDF-N at $z > 4$ are likely related to the smallest cold dark matter haloes. In hierarchical large-scale structure formation, these small haloes collapse earlier than the larger ones, thus effectively tracing the first massive structures to form in the Universe.

The Galactic column density along the line of sight to these sources is 1.6×10^{20} cm^{-2} (Stark et al. 1992). In this Letter $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_{\rm M}$=0.3, and Ω_Λ=0.7 are adopted.

2. X-RAY OBSERVATIONS AND THE SAMPLE OF $z > 4$ AGNS

The X-ray results were obtained with ACIS-I (the imaging array of the Advanced CCD Imaging Spectrometer; Garmire et al. 2002) onboard *Chandra*. The 2 Ms CDF-N observations were centered on the Hubble Deep Field-North (HDF-N; Williams et al. 1996) and cover ≈ 460 arcmin^2. They reach on-axis 0.5–2.0 keV (soft-band) and 2–8 keV (hard-band) flux limits of $\approx 1.5 \times 10^{-17}$ erg cm^{-2} s^{-1} and $\approx 1.0 \times 10^{-16}$ erg cm^{-2} s^{-1}, respectively. The 2 Ms data processing and the derived X-ray catalog are described in D. M. Alexander et al., in preparation.

We investigate here the X-ray properties of the three $z > 4$ AGNs spectroscopically identified in the CDF-N: the $z = 5.186$ quasar CXOHDFN J123647.9+620941 (Barger et al. 2002, hereafter B02; $M_{\rm B} \approx -23.4$), and the two Seyfert galaxies CXOHDFN J123719.0+621026 (B02; $M_{\rm B} \approx -21.4$) and CXOHDFN J123642.0+621331 (VLA J123642+621331; Waddington et al. 1999, hereafter W99; Brandt et al. 2001b; $M_{\rm B} \approx -21.6$) at $z = 4.137$ and $z = 4.424$, respectively; the latter Seyfert galaxy is the only object in our sample with detected radio emission (0.47 mJy at 1.4 GHz; Richards 2000). Only one object (CXOHDFN J123719.0+621026) shows hints of X-ray variability by a factor of ≈ 2 over the ≈ 27-month interval covered by the 20 X-ray observations that comprise the 2 Ms exposure (F. E. Bauer et al., in preparation). We note, however, that our X-ray constraints are weak because of the low counting statistics in each observation. A summary of the principal optical and X-ray properties of the three AGNs is presented in Table 1.

We would expect there to be further unidentified $z > 4$ AGNs in the CDF-N. For instance, using the surface density of $z > 4$ quasars in the Sloan Digital Sky Survey (SDSS) Early Data Release quasar catalog (Schneider et al. 2002) and the luminosity function derived from $z \approx 4.3$ SDSS quasars (Fan et al. 2001b), we would expect ≈ 7 (0.5) AGNs over the CDF-N field down to $M_{\rm B} = -21.4$ (-23.4). This is likely to be a lower limit since this calculation does not take into account narrow-lined AGNs. All of the sources within $\approx 10'$–$12'$ of

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TABLE 1
PROPERTIES OF $z > 4$ AGNS IN THE CDF-N

Object Name	z	I−band mag	$AB_{1450(1+z)}$[a] mag	M_B	Counts[b] (0.5–2 keV)	Counts[b] (0.5–8 keV)	0.5–8 keV Effective Exposure (ks)	Count rate[c] (0.5–2 keV)	Count rate[c] (0.5–8 keV)	Off-axis angle (′)
CXOHDFN J123642.0+621331	4.424	24.9[d]	25.1	−21.6	$31.0^{+7.3}_{-6.1}$	$44.6^{+8.9}_{-7.7}$	1929.5	$1.61^{+0.38}_{-0.32}$	$2.31^{+0.46}_{-0.40}$	0.6
CXOHDFN J123647.9+620941	5.186	23.1[e]	23.5	−23.4	$96.7^{+11.7}_{-10.5}$	$137.9^{+14.6}_{-13.3}$	1814.0	$5.34^{+0.64}_{-0.58}$	$7.60^{+0.81}_{-0.73}$	4.3
CXOHDFN J123719.0+621026	4.137	25.0[e]	25.2	−21.4	$83.1^{+11.3}_{-10.1}$	$117.4^{+14.2}_{-13.0}$	1769.8	$4.70^{+0.64}_{-0.57}$	$6.63^{+0.81}_{-0.73}$	5.2

[a] $AB_{1450(1+z)}$ magnitudes have been derived from the I−band magnitudes using extrapolations, i.e., an ultraviolet/optical slope of α=−0.5 ($S_\nu \propto \nu^\alpha$). [b] Source counts and 1σ statistical errors (from Gehrels 1986) have been calculated using circular aperture photometry; these values have been taken from the 2 Ms X-ray catalog (D. M. Alexander et al., in preparation). The number of 0.5–8 keV counts reported here may be different from that used in the spectral analysis because of the different methods adopted in their computation; see F. E. Bauer et al., in preparation, for further discussion. [c] Observed count rate (corrected for vignetting using the exposure maps), in units of 10^{-5} counts s^{-1}. [d] I−band magnitude from W99. [e] I−band magnitude from B02.

the aimpoint should be detectable at X-ray energies [assuming $\alpha_{\rm ox}$=−1.48 (see §4), we predict soft (0.5–2 keV) X-ray fluxes of $\approx$(6–8)$\times10^{-17}$ erg cm^{-2} s^{-1}]. However, with predicted optical magnitudes down to $I \approx 25$, many will be optically faint and challenging to identify (e.g., Alexander et al. 2001).

3. X-RAY SPECTRAL ANALYSIS

Given the deep exposure and the low (but non-negligible) background of the ACIS instrument, we are able to perform direct spectral analyses for the sources in our sample. Since the 20 separate observations that comprise the 2 Ms CDF-N are characterized by different roll angles and aimpoints, we used the source extraction code (ACIS EXTRACT[3]) described in P. S. Broos et al. (2002). For each source, this code extracts the counts from each of the 20 observations, taking into account the dependence in shape and size of the Point Spread Function (PSF) with off-axis angle as given in the *Chandra* X-ray Center (CXC) PSF library.[4] For the sources investigated here, events are extracted using the 90% encircled energy regions measured at 1.5 keV (at the position of each source). The background was chosen locally after all sources were excluded from the X-ray event file. Visual inspection of the X-ray images shows that the three AGNs are not contaminated by nearby X-ray sources. To account for the quantum efficiency degradation of ACIS[5] at low energies ($\approx$ 10% at 1 keV), possibly caused by molecular contamination of the ACIS filters, we have applied a time-dependent correction to the ACIS quantum efficiency generating a corrected ancillary response file (ARF) for each data set (G. Chartas et al., in preparation).[6] An energy-dependent aperture correction was also applied to each ARF. Spectra and response matrices, weighted by the number of counts in each observation, were summed using standard FTOOLS routines (Blackburn 1995).

Spectral analysis was carried out with XSPEC (Version 11.2.0; Arnaud 1996); the uncertainties on spectral parameters are quoted at the 90% confidence level for one interesting parameter (i.e., $\Delta\chi^2$=2.71; Avni 1976). Given the limited counting statistics, we performed the spectral analysis using the unbinned, background-subtracted source spectra and the Cash statistic (Cash 1979). The Cash statistic is well suited to low-count sources (e.g., Nousek & Shue 1989), and in the latest version of XSPEC it is possible to use it with background-subtracted data (Arnaud 2002). Several checks of the background-subtraction method were carried out to verify that no spurious residual features were present in the background-subtracted data. One limitation of the Cash statistic is that it does not provide a quality-of-fit criterion (like the χ^2 statistic) to compare different models. Therefore, we established the quality of the spectral results via visual inspection using the binned spectrum. In the spectral fitting we have assumed solar abundances, although there are indications of supersolar abundances of heavy elements in high-redshift quasar nuclei (e.g., Hamann & Ferland 1999; Constantin et al. 2002). Choosing different abundances provides changes in the column density and Fe Kα line measurements. For example, doubling the abundances in the fit gives a reduction in the column density by $\approx$ 50% and a small increase (a few %) in the iron Kα line intensity (see Fig. 17 of George & Fabian 1991).

3.1. *Spectral analysis results*

CXOHDFN J123647.9+620941 is the only $z > 5$ quasar having an X-ray spectrum with more than 100 counts to date. Spectral fitting in the observed-frame 0.5–8 keV band (Fig. 1) shows that this source is well parameterized by a power-law continuum with photon index $\Gamma = 1.81^{+0.31}_{-0.29}$ (see Table 2). This photon index is similar to those of $z \approx$ 0–2 AGNs, which have typical photon indices of $\Gamma \approx$ 1.7–2.3 in the rest-frame 2–10 keV band (e.g., George et al. 2000; Reeves & Turner 2000).

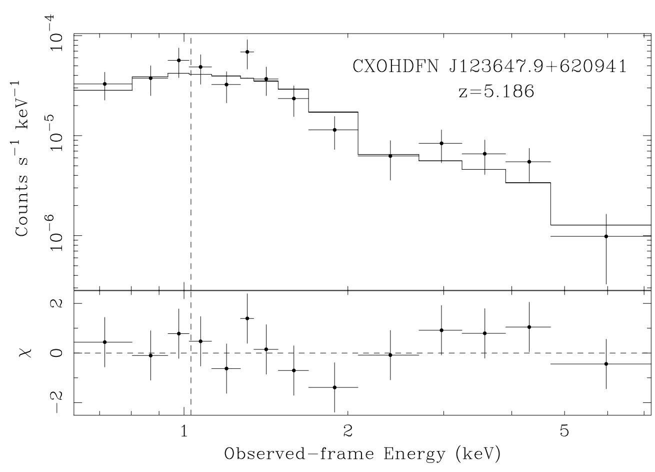

FIG. 1.— CXOHDFN J123647.9+620941 spectrum (binned to 10 counts per bin for presentation purposes) with the best-fit $\Gamma = 1.81$ power law and Galactic absorption. Data-to-model residuals are shown in the bottom panel (in units of σ). The dashed vertical line indicates the observed-frame energy for a neutral Fe Kα emission line.

[3] ACIS EXTRACT is a part of the TARA software package and can be accessed from http://www.astro.psu.edu/xray/docs/TARA/ae_users_guide.html.

[4] See http://asc.harvard.edu/ciao2.2/documents_dictionary.html#psf.

[5] See http://cxc.harvard.edu/cal/Links/Acis/acis/Cal_prods/qeDeg/index.html.

[6] See http://www.astro.psu.edu/users/chartas/xcontdir/xcont.html.

TABLE 2
X-RAY SPECTRAL RESULTS

Object Name	PL – Γ	PL+ABS				Flux[a]			
		Γ	$N_{\rm H,z}$ (cm^{-2})	$N^{\rm b}_{\rm H,z}$ (cm^{-2})	Fe Kα EW[c] (eV)	(0.5–2 keV)	(0.5–8 keV)	$\log(L_{2-10\ \rm keV})$[d]	$\alpha_{\rm ox}$[e]
CXOHDFN J123642.0+621331	$1.55^{+0.61}_{-0.54}$	$1.55^{+0.61}_{-0.54}$	$< 4.82 \times 10^{22}$	$< 6.85 \times 10^{22}$	< 400	0.9	2.7	43.2	−1.52
CXOHDFN J123647.9+620941	$1.81^{+0.31}_{-0.29}$	$1.76^{+0.41}_{-0.25}$	$< 7.47 \times 10^{22}$	$< 9.48 \times 10^{22}$	< 700	2.9	6.8	43.9	−1.51
CXOHDFN J123719.0+621026	1.12 ± 0.25	$1.34^{+0.34}_{-0.33}$	$< 1.64 \times 10^{23}$	$1.90^{+0.94}_{-0.76} \times 10^{23}$	< 660	2.6	11.8	43.4	−1.41

NOTE. — "PL" means a power-law model and Galactic absorption; "PL+ABS" indicates that additional neutral absorption at the source redshift has been used in the spectral fitting.
[a] Observed-frame flux derived from the X-ray spectral analysis, in units of 10^{-16} erg cm^{-2} s^{-1} . [b] Intrinsic column density computed assuming $\Gamma = 2.0$. [c] Rest-frame. [d] 2–10 keV rest-frame luminosity corrected for Galactic absorption, in units of erg s^{-1}. [e] $\alpha_{\rm ox} = \frac{\log(f_{2\ \rm keV}/f_{2500\ \mathring{A}})}{\log(\nu_{2\ \rm keV}/\nu_{2500\ \mathring{A}})}$, where $f_{2\ \rm keV}$ and $f_{2500\ \mathring{A}}$ are the flux densities at rest-frame 2 keV and 2500 Å. The monochromatic flux densities have been derived from the $I-$band magnitudes (using α=−0.5) and the observed-frame, Galactic absorption-corrected 0.5–2 keV flux (using the photon index reported in the second column).

There is no evidence for either intrinsic absorption or Fe Kα emission lines (see Table 2). The optical spectrum of CXOHDFN J123647.9+620941 shows a Lyα emission line (B02) whose FWHM appears significantly smaller than those typical of optically selected, optically bright, high-redshift quasars (e.g., Fan et al. 2001a). The lack of flux calibration in the spectrum of B02 prevents a more precise comparison.

CXOHDFN J123719.0+621026 is characterized by a flat effective X-ray photon index ($\Gamma = 1.12 \pm 0.25$), which provides an acceptable fit to our data. There are two possible explanations for this result, both consistent with our data: CXOHDFN J123719.0+621026 has either an intrinsically flat X-ray spectrum or a steeper ($\Gamma \approx 2.0$) X-ray spectrum plus absorption. Based on previous results for low- and intermediate-redshift quasars (e.g., George et al. 2000; Reeves & Turner 2000), optically luminous $z > 4$ quasars (V03), and CXOHDFN J123647.9+620941, we suggest that the underlying continuum is likely a $\Gamma \approx 2.0$ power law. When the photon index is fixed to 2, a deficit of X-ray counts is visible below ≈ 3 keV (see Fig. 2).

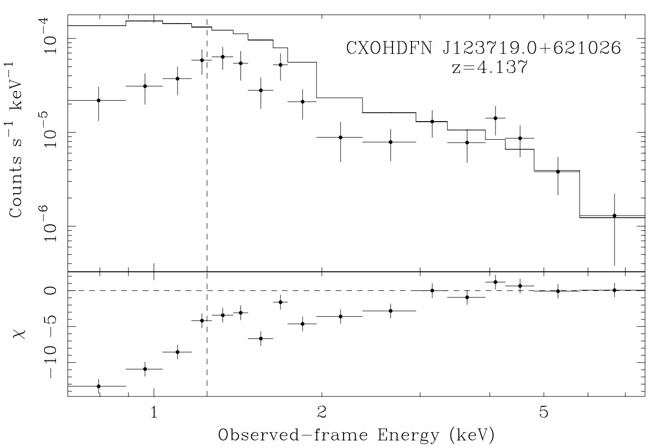

FIG. 2.— CXOHDFN J123719.0+621026 spectrum (binned to 10 counts per bin for presentation purposes) fitted above 3 keV with a $\Gamma = 2$ power-law model that has been extrapolated back to lower energies. Data-to-model residuals are shown in the bottom panel (in units of σ). A deficit of counts below ≈ 3 keV is present. The dashed vertical line indicates the observed-frame energy for a neutral Fe Kα emission line.

This suggests the presence of a column density of $\approx 2{\times}10^{23}$ cm^{-2} (see Table 2), typical of local Compton-thin Seyfert 2 galaxies (e.g., Bassani et al. 1999). The upper limit on the neutral Fe Kα emission-line equivalent width (rest-frame $EW < 660$ eV) allows us to rule out the possibility that the X-ray emission is due purely to a scattered/reflected component from a Compton-thick source (i.e., a source with a column density larger than 1.5×10^{24} cm^{-2}; e.g., Matt et al. 2000), since in this case a strong ($EW \gtrsim 1$ keV) iron Kα line at 6.4 keV is expected (e.g., Matt, Brandt, & Fabian 1996; Maiolino et al. 1998). The flat $\alpha_{\rm ox}$ value (see Table 2 and §4) suggests that the AGN is comparitively weak at optical wavelengths; the presence of a narrow Lyα line supports this suggestion.

CXOHDFN J123642.0+621331 is the faintest X-ray source in our sample and lies just outside the HDF-N. Detailed studies of this source indicate a redshift of $z = 4.424$ (W99; R. A. Windhorst 2001, private communication; but also see §2.2 of Barger, Cowie, & Richards 2000). The presence of an AGN is suggested by multi-wavelength studies. The apparent radio jet in the combined MERLIN/VLA image (W99) indicates the presence of an AGN, as does the source's large 1.4 GHz radio luminosity ($\approx 7.8 \times 10^{32}$ erg s^{-1} Hz^{-1}), which is more typical of AGNs than starburst galaxies (e.g., Bauer et al. 2002). From an X-ray perspective, Brandt et al. (2001b), based on a 480 ks *Chandra* observation, argued that its X-ray-to-optical flux ratio and X-ray luminosity were suggestive of the presence of an active nucleus. This is confirmed by the 2 Ms results reported in this Letter. In particular, the detection of CXOHDFN J123642.0+621331 in the 2–8 keV band (corresponding to the rest-frame $\approx$ 11–43 keV band) strongly supports the presence of an active nucleus rather than only a starburst. The relatively flat X-ray spectrum ($\Gamma = 1.55^{+0.61}_{-0.54}$) can be due either to the presence of intrinsic absorption (not constrained by the present observation; see Table 2) or to the radio loudness of this source.[7] In fact, previous studies (e.g., Wilkes & Elvis 1987; Cappi et al. 1997) indicate that jet emission can give rise to flatter slopes in the X-ray band because of synchrotron or synchrotron self-Compton emission.

4. BROAD-BAND COMPARISONS WITH OTHER $z \geq 4$ AGNS

Presently, ≈ 50 $z \geq 4$ quasars have X-ray detections (see Brandt et al. 2002b and V03 for the most recent results).[8] Figure 3 shows the observed-frame, Galactic absorption-corrected 0.5–2 keV flux versus $AB_{1450(1+z)}$ magnitude for a compilation of $z \geq 4$ AGNs (most of these are radio-quiet quasars; RQQs) with X-ray detections or upper limits. The majority of the objects shown in Fig. 3 are optically selected

[7] Its radio loudness, parameterized by $R = f_{5\ \rm GHz}/f_{4400\ \mathring{A}}$ (rest frame; e.g., Kellermann et al. 1989), is ≈ 1200.

[8] Also see http://www.astro.psu.edu/users/niel/papers/highz-xray-detected.dat for a regularly updated compilation of X-ray detected $z \geq 4$ AGNs.

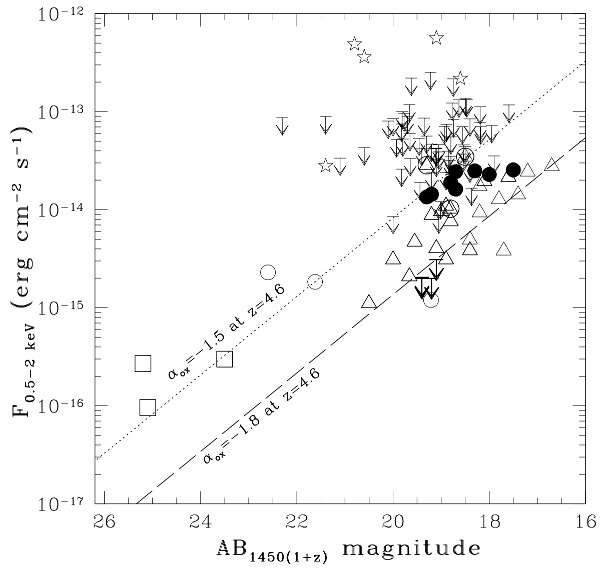

FIG. 3.— Observed-frame, Galactic absorption-corrected 0.5–2 keV flux versus $AB_{1450(1+z)}$ magnitude for $z \geq 4$ AGNs. The three $z > 4$ AGNs in the CDF-N are plotted as open squares. Open triangles and thick downward-pointing arrows indicate *Chandra* observations of $z \geq 4$ quasars (V01; V03; Brandt et al. 2002a; Bechtold et al. 2002); circled triangles are radio-loud quasars. The quasars with *ROSAT* detections or upper limits are plotted as filled circles and thin downward-pointing arrows, respectively (Kaspi et al. 2000; V01; V03); blazars are shown as open stars. Open circles show X-ray detected AGNs from other work (Schneider et al. 1998; Brandt et al. 2001a; Silverman et al. 2002). For comparison, the slanted lines show $z = 4.6$ loci for α_{ox}=−1.5 (dotted) and α_{ox}=−1.8 (dashed).

and populate the bright (upper right) region of the plot. By contrast, the sources under investigation in this Letter (open squares) populate the faint (lower left) region. At present, the study of the properties of such faint sources via X-ray spectral analysis is possible only with deep *Chandra* and XMM-*Newton* exposures.

Figure 3 shows that the optically selected quasars have, on average, steeper α_{ox} than the X-ray selected AGNs in our sample, as expected because of the different selection criteria and the anti-correlation found between α_{ox} and rest-frame 2500 Å luminosity (e.g., Vignali, Brandt, & Schneider 2003). Using ASURV (LaValley, Isobe, & Feigelson 1992) to take into account the X-ray upper limits, we derive $\langle\alpha_{ox}\rangle$=$-1.74\pm0.02$ (the errors represent the standard deviation of the mean) for the sample of $z \geq 4$ optically selected RQQs observed by *Chandra* to date (see V03). The sample of three $z > 4$ AGNs in the CDF-N have $\langle\alpha_{ox}\rangle$=$-1.48\pm0.03$. Excluding CXO-HDFN J123642.0+621331 because of its radio selection and including the X-ray selected quasars in the Lockman Hole (Schneider et al. 1998; $z = 4.45$) and ChaMP survey (Silverman et al. 2002; $z = 4.93$), we find $\langle\alpha_{ox}\rangle$=$-1.42\pm0.04$.

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